

# Local Group Dwarf Galaxies: Nature *And* Nurture

Till Sawala<sup>1,3\*</sup>, Cecilia Scannapieco<sup>2</sup>, and Simon White<sup>3</sup>

<sup>1</sup>*Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*

<sup>2</sup>*Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany*

<sup>3</sup>*Max-Planck Institute for Astrophysics, Karl-Schwarzschild-Strasse 1, 85748 Garching, Germany*

Accepted \*\*\*. Received \*\*\*; in original form 09 March 2011

## ABSTRACT

We investigate the formation and evolution of dwarf galaxies in a high resolution, hydrodynamical cosmological simulation of a Milky Way sized halo and its environment. Our simulation includes gas cooling, star formation, supernova feedback, metal enrichment and UV heating. In total, 90 satellites and more than 400 isolated dwarf galaxies are formed in the simulation, allowing a systematic study of the internal and environmental processes that determine their evolution. We find that 95% of satellite galaxies are gas-free at  $z = 0$ , and identify three mechanisms for gas loss: supernova feedback, tidal stripping, and photo-evaporation due to re-ionization. Gas-rich satellite galaxies are only found with total masses above  $\sim 5 \times 10^9 M_\odot$ . In contrast, for isolated dwarf galaxies, a total mass of  $\sim 10^9 M_\odot$  constitutes a sharp transition; less massive galaxies are predominantly gas-free at  $z = 0$ , more massive, isolated dwarf galaxies are often able to retain their gas. In general, we find that the total mass of a dwarf galaxy is the main factor which determines its star formation, metal enrichment, and its gas content, but that stripping may explain the observed difference in gas content between field dwarf galaxies and satellites with total masses close to  $10^9 M_\odot$ . We also find that a morphological transformation via tidal stripping of infalling, luminous dwarf galaxies whose dark matter is less concentrated than their stars, cannot explain the high total mass-light ratios of the faint dwarf spheroidal galaxies.

**Key words:** cosmology: theory – galaxies: dwarf – galaxies: Local Group – galaxies: formation – galaxies: evolution – methods: N-body simulations

## 1 INTRODUCTION

The Milky Way galaxy is believed to be surrounded by hundreds of dwarf galaxies (Koposov et al. 2008; Tollerud et al. 2008). Most of the known satellites are faint, early type dwarf spheroidal galaxies, with stellar masses ranging from less than  $10^3$  up to  $10^7 M_\odot$ , predominantly old and metal-poor stellar populations, no detectable interstellar gas, and eponymous, spheroidal morphologies. Stellar kinematics suggest that dwarf spheroidal galaxies are dominated by dark matter (Faber & Lin 1983), with estimates for the total dynamical masses in the range of  $\sim 2 \times 10^8 - 10^9 M_\odot$  (Walker et al. 2007).

Dwarf galaxies of such low total mass are believed to be highly susceptible to both external and internal effects: Supernova feedback can establish a self-regulation of star formation, and also lead to an ejection of gas, while the interaction with the environment, and with neighbouring galaxies, can potentially strip their interstellar gas, and may also change their morphology. The effect of the cosmological UV-

background, whilst external, is assumed to be independent of environment, and therefore identical for satellites and for isolated dwarf galaxies.

Since the correlation of morphological type with proximity to larger galaxies was first demonstrated by Einasto et al. (1974), the role of *Nature* versus *Nurture* in the formation of early-type dwarf galaxies has been the cause of debate (e.g. Mateo 1998; Grebel et al. 2003; Tolstoy et al. 2009; Annibali et al. 2010). Evidence for environmental effects on galaxy formation in general is well known, and expressed in the morphology-density relation (e.g. Davis & Geller 1976). Two studies comparing early type dwarf galaxies in the field to early type dwarf galaxies in clusters (Michielsen et al. (2008) for the Virgo cluster and Koleva et al. (2009) for the Fornax cluster), found no clear difference between the environments. However, comparing Coma cluster dwarf galaxies to dwarf galaxies in poor groups, Annibali et al. (2010) reported that dwarf galaxies in low-density environments may experience more prolonged star formation; evidence that the morphology-density relation also extends to dwarf galaxies. It should also be emphasized that even if the environmental correlation is weak, ex-

\* E-Mail: till.sawala@durham.ac.uk

ternal effects could still play an important role if, for dwarfs, the responsible mechanisms are also efficient in low-density environments.

In a sample of SDSS galaxies with stellar masses in the range of  $2 \times 10^7 - 3 \times 10^8 M_\odot$ , Geha et al. (2006) report that the gas fraction of dwarf galaxies increases with distance to their nearest luminous neighbour. Within the Local Group, Einasto et al. (1974) show that the HI mass in dwarf galaxies follow a similar trend with distance to M31 or the Milky Way. Grebel et al. (2003) also report a morphology-distance relation: late-type, dwarf irregular galaxies are found predominantly at the outskirts of the Local Group; early type dwarf galaxies are mostly satellites; so-called transition type galaxies, which share some of the characteristics of early type dwarf galaxies whilst also containing some gas, are found at intermediate distances. Grebel (1997) also find a correlation between galactocentric distance and duration of star formation in Milky Way satellites.

On the other hand, there is also evidence for supernova-driven outflows in starburst dwarf galaxies (e.g. Meurer et al. 1992; Schwartz & Martin 2004). Sánchez-Janssen et al. (2010) conclude that low-mass galaxies tend to be less strongly affected by tidal forces, and that the morphological trend of increasing thickness found in fainter galaxies, is related to the increasing importance of feedback mechanisms, rather than environmental effects.

Future studies of isolated dwarf galaxies in the Local Group may answer the question whether internal processes suffice to expel gas from dwarf galaxies, or whether interactions are a necessary factor. Two isolated dwarf spheroidal galaxies, Cetus (Whiting et al. 1999) and Tucana (Lavery & Mighell 1992), have been discovered in the Local Group, with distances of  $780 \pm 40$  kpc and  $890 \pm 50$  kpc, respectively (Bernard et al. 2009). Deep observations and modeling of the stellar populations by Monelli et al. (2010) suggests that these presently isolated objects are similar to the oldest Milky Way dSph satellites; this runs counter to the morphology density relation and suggests a formation mechanism independent of environment. However, it is not known with certainty whether present isolation also implies isolated evolution.

Numerical simulations of isolated dwarf galaxies (e.g. Stinson et al. 2007; Valcke et al. 2008; Revaz et al. 2009; Sawala et al. 2010) have shown that dark matter-dominated, early-type dwarf galaxies comparable to the Local Group dwarf spheroidals *can* form in isolation through the processes of supernova feedback and UV radiation, which regulate and eventually quench star formation, and eject most of the interstellar gas. In particular, this work showed that the dependence of the efficiency of the two effects on the depth of the gravitational potential can explain the observed scaling relations between stellar mass and mass-to-light ratio (e.g. Mateo 1998; Gilmore et al. 2007; Strigari et al. 2008), and between stellar mass and metallicity (Grebel et al. 2003; Tolstoy et al. 2009).

Simulations of interacting dwarfs (Mayer et al. 2001, 2006; Klimontowski et al. 2009) have indicated that evolved, disk-like galaxies can also be transformed into fainter, early-type dwarf galaxies in the environment of the Milky-Way. Two mechanisms that can lead to such a transformation are ram pressure and tidal interactions.

Ram pressure refers to the pressure exerted on the inter-

stellar gas of a satellite galaxy as it passes through the hot intergalactic medium in a dense environment (Einasto et al. 1974). Ram-pressure stripping affects the interstellar gas, but not the stars or dark matter. While this mechanism is observable in galaxy clusters, estimates of the gas density of the Milky-Way halo (e.g. Murali 2000) show it to be several orders of magnitude too low for ram pressure stripping to be efficient (Mayer et al. 2001).

Tidal perturbations are caused by the differential gravitational acceleration across the diameter of a satellite as it orbits the main halo. They affect gas, stars and dark matter alike, and can alter the internal kinematics and morphology of the satellite (“tidal distortion”), as well as remove mass from the objects (“tidal stripping”). Tidal stripping can still change the composition of objects, if the spatial distribution of the components differ. Clear observational evidence for tidal stripping within the Milky-Way halo is provided by the presence of tidal streams (e.g. Johnston et al. 1999, now also observed around other galaxies). These elongated substructures consist of stars that were tidally unbound from satellite galaxies, and deposited along their orbits.

Most present day dwarf spheroidals, however, show no sign of tidal distortion in their stellar kinematics (Walker et al. 2007). Models in which similar-mass late type progenitors are transformed into different-mass dwarf spheroidals based on orbital parameters alone, may have also difficulty in explaining the strong-mass metallicity scaling relation (Grebel et al. 2003). Most dwarf spheroidals also show metallicity gradients, which are reproduced in simulations where star formation is regulated by internal processes (Revaz et al. 2009), but are not typically found in dwarf irregulars, and may not be preserved during strong tidal stirring.

So far, simulations have largely separated internal and external mechanisms: by investigating either the formation of isolated dwarf galaxies (Stinson et al. 2007; Valcke et al. 2008; Revaz et al. 2009; Sawala et al. 2010), or the transformation of evolved objects in an external gravitational potential (Mayer et al. 2001, 2006; Klimontowski et al. 2009). In reality, all effects are simultaneously present in the Local Group. In this work, we present results from the *Aquila* Simulation (Scannapieco et al. 2009), which follows the formation of a Milky Way sized galaxy and its environment in the fully cosmological context of a  $\Lambda$ CDM universe. The satellites that grow and evolve are thus subject to tidal forces, but also all the astrophysical processes associated with cooling, star formation, supernova feedback and UV heating. This simulation allows us to study all these effects in a consistent manner, and to compare their relative importance for the evolution of each object individually, as well as for the ensemble of the Milky Way satellites.

This paper is organized as follows: Section 2 contains a description of the initial conditions for the simulation, the numerical methods, and the method for the identification of substructure. Section 3 describes the formation and time-evolution of the halo along with its substructures. In Section 4 we take a closer look at the different mechanisms for gas removal in individual satellites. Section 5 summarizes the statistical properties of the present-day satellite population and the derived scaling relations. In Section 6, we also compare the population of satellites to the population of

isolated dwarf galaxies formed in the same simulation. We conclude with a summary in Section 7.

## 2 THE AQUILA SIMULATION

The simulation was set up with the principal aim of studying the formation of disk galaxies in a  $\Lambda$ CDM universe. The results presented here are based on simulation “AQ-C-5” of Scannapieco et al. (2009), which resulted in the formation of a Milky-Way sized disk galaxy. In this paper, the focus is on the formation and evolution of the  $\sim 90$  satellites of the central galaxy, and the isolated dwarf galaxies that form in its environment.

### 2.1 Initial Conditions

The initial conditions used here are based on one of several haloes (labeled halo “C”), which were extracted from the Millennium II Simulation, and resimulated with pure dark matter in the *Aquarius* project (Springel et al. 2008). The cosmological parameters are identical to those of the Millennium Simulations,  $\Omega_m = 0.25$ ,  $\Omega_\Lambda = 0.75$ ,  $h = 0.73$  and  $\sigma_8 = 0.9$ , consistent with WMAP-1 cosmology. The simulation is performed with periodic boundary conditions in a box of side length 137 Mpc ( $100h^{-1}$  Mpc in comoving coordinates). The central Lagrangian region is filled with an equal number of high resolution dark matter and gas particles, at a mass ratio of  $\Omega_{DM} = 0.21$  to  $\Omega_b = 0.04$ . The particle masses in the level 5 *Aquila* simulation are  $2.6 \times 10^6 M_\odot$  for dark matter and  $2\text{--}4 \times 10^5 M_\odot$  for gas particles. Star particles which form have a mass of  $1\text{--}2 \times 10^5 M_\odot$ . The gravitational softening parameter is fixed to  $1.37 (1h^{-1} \text{ kpc})$  in comoving coordinates, and equal for all particle types. Throughout this paper, masses and distances will be stated in physical units of  $M_\odot$  and kpc. Note that despite the limited accuracy of gravitational forces at the softening scale, tidal accelerations due to an external potential are almost unaffected by the softening.

### 2.2 Computational Methods

The simulations are performed with the smoothed particle hydrodynamics code GADGET-3 (Springel 2005; Springel et al. 2008), together with the star formation, feedback and multiphase ISM model of Scannapieco et al. (2005, 2006). The same model is also used in the higher resolution simulations of isolated dwarf galaxies presented in Sawala et al. (2010, 2011). Specific to this simulation, a star formation parameter of  $c_\star = 0.1$  is used, whereas most simulations presented in Sawala et al. (2010), and all simulations of Sawala et al. (2011) use a value of  $c_\star = 0.05$ . Sawala et al. (2010) also contains a discussion of the effect of varying  $c_\star$  for dwarf galaxies. The energy per supernova is set to  $0.7 \times 10^{51}$  ergs, identical to the value of Sawala et al. (2011), but slightly lower than the value of  $1.0 \times 10^{51}$  ergs used in Sawala et al. (2010). The energy and metals are distributed equally between the hot and cold gas phases. The cooling model is based on Sutherland & Dopita (1993), with no cooling below  $10^4 K$ , and the UV heating mechanism is implemented following Haardt & Madau (1996), assuming a cosmic UV background active from  $z = 6$ .

The mass resolution of the *Aquila* simulation is several hundred times lower than can be achieved in simulations of individual dwarf galaxies. This reflects primarily the much larger Lagrangian volume, but the presence of a large galaxy with its high cold gas fraction and specific star formation rate also increases the computational cost per particle. As a result, the properties of individual dwarf galaxies are not resolved with the same level of detail as in simulations of isolated objects; dwarf galaxies with stellar masses of  $\sim 10^6 M_\odot$  are clearly stretching the resolution limit. Still, the large number of satellites that form allow a number of statistical comparisons. In addition, the fact that, apart from the differences stated above, the same astrophysical and numerical models are used in the high resolution simulations of Sawala et al. (2010, 2011), allows a direct comparison and an estimation of the effects of resolution. We include the results of our high-resolution simulations in Figure 8.

The same initial conditions have also been used in other studies (Okamoto & Frenk 2009; Okamoto et al. 2010; Wadepuhl & Springel 2010), with different physical astrophysical models and numerical codes. The star formation and feedback model of Wadepuhl & Springel is based on Springel & Hernquist (2003), combined with a black hole wind model and a model for cosmic rays. They conclude that cosmic rays, or some other mechanism in addition to thermal supernova feedback and UV heating is necessary in order to bring the satellite luminosity function in agreement with observations. Our results agree qualitatively with their simulations, despite the fact that we do not include cosmic rays, indicating that supernova feedback produces similar effects in our ISM model to cosmic ray pressure in theirs. Okamoto et al. investigate how varying the treatment of feedback affects the properties of dwarfs. They show that stellar mass and metallicity scale strongly with circular velocity (i.e. subhalo mass), and conclude that a threshold established by re-ionization results in the small fraction of visible satellite galaxies populating a much larger number of satellite subhaloes. Neither study investigates the *isolated* dwarfs and compares them to the satellites; this is a major part of our work.

### 2.3 Identification of Substructure

In each snapshot, haloes are identified in a two step process using a Friend-of-Friend (FoF) algorithm. The FoF groups are defined first by linking only the dark matter particles. In a second step, star and gas particles are linked to the particles already belonging to these groups in the same way. In the *Aquila* simulation, the larger haloes, and in particular, the main halo that will become the host of the “Milky Way” galaxy, also contain a number of gravitationally bound, over-dense substructures called *subhaloes*, which are identified using the SUBFIND algorithm of Springel et al. (2001). For each FoF halo, SUBFIND begins by computing a smoothed local density by an SPH-interpolation over all particles of the halo. A potential substructure is first identified as a local overdensity with respect to this smooth background density. It is then subjected to gravitational unbinding, whereby all unbound particles are iteratively removed, until the substructure either vanishes, falling below the threshold of 20 particles, or is identified as a genuine self-bound subhalo.

In order to trace subhaloes over time between different

snapshots, the 20 most bound dark matter particles of each subhalo in a given snapshot were compared to the list of particles in all subhaloes of the previous snapshot, identifying as the progenitor the subhalo that contained at least 11 of the 20 particles amongst its 20% of most bound particles. The process is repeated until a progenitor is no longer found, and we define this as the time of *formation*. If the subhalo can be linked to a subhalo in a previous snapshot, but not to its most bound particles, we consider the progenitor to have fragmented, and define this as the time of *fragmentation*. Fragmentation can be due to the breaking-up of larger haloes, or to the amplification of substructures above the particle threshold, without the newly identified subhaloes hosting galaxies. In Table 1, fragmentation is indicated with an asterisk next to the formation redshift. We note that a large majority of subhaloes of satellite galaxies can be traced back as independent objects well beyond  $z = 6$ .

Most of the subhaloes belonging to the main halo at  $z = 0$  belong to different groups at earlier times. We call the time when a subhalo is *first* identified as a subhalo of the main halo the time of *infall*, noting that some subhaloes subsequently become transitorily isolated, and fall in again at a later time.

### 3 TIME EVOLUTION OF THE AQUILA SIMULATION

Figures 1, 2 and 3 respectively show the time-evolution of the projected dark matter, gas and stellar mass distributions in the central region of the simulation. Each panel is centred on the position of the main subhalo (which is the host of the “Milky Way”), and shows all particles within a cubic volume of side length 1 Mpc. At each redshift, the  $X, Y$  and  $Z$ -coordinates are defined parallel to the principal moments of the inertia tensor of the halo, with eigenvalues  $I_x > I_y > I_z$ . Keeping the volume fixed in comoving coordinates corresponds to a zoom-out in physical coordinates by a factor of 7.5 as the universe grows with time from  $z = 6.5$  to  $z = 0$ . The squares indicate the position of all satellite subhaloes belonging to the main FoF halo identified at the time of the snapshot, with the size of the squares in all figures indicative of (but not strictly proportional to) the dark matter mass of the subhalo.

In Figure 2, where the blue colour indicates gas density, red boxes denote the subhaloes that contain gas, while white boxes denote subhaloes that are gas-free. It can be seen that even at high redshifts, the majority of subhaloes are gas-free, and only four relatively massive satellites contain gas at  $z = 0$ . The smallest of these four satellites, which are the subject of Section 4.3, has a total mass of  $\sim 5 \times 10^9 M_\odot$ . All lower mass satellites, many of which formed stars, have lost their gas during their evolution. The different mechanisms of gas loss, internal and environmental, are discussed in Section 4.

In Figure 3, the green colour shows the stellar density, which is clearly dominated by the central object and its halo. Here, red boxes show subhaloes that contain stars, while white boxes show haloes that are essentially dark. At  $z = 0$ , there are 90 subhaloes containing stars, including the four which contain gas, as shown in Figure 2. The highest mass subhalo that does not contain any stars at  $z = 0$  has a mass of  $4.3 \times 10^8 M_\odot$ . The lower mass limit for star formation

becomes difficult to assess, because of the limited resolution of our simulation. The total number of subhaloes with stars is comparable, however, with observational estimates of the number of dwarf satellites around the Milky Way.

The halo reaches a final virial mass of  $1.6 \times 10^{12} M_\odot$ , comparable to recent observational estimates of the Milky Way halo, for example  $10^{12} M_\odot$  (Xue et al. 2008),  $1.4 \times 10^{12} M_\odot$  (Smith 2007),  $1.6 \times 10^{12} M_\odot$  (Gnedin et al. 2010) and  $2.4 \times 10^{12} M_\odot$  (Li & Helmi 2008). The corresponding spherical virial radius is  $\sim 250$  kpc, but we include as satellites all subhaloes within the FoF group. 40% of the satellites are presently located outside of  $r_{vir}$ , with the furthest satellite at a galactocentric distance of 490 kpc. The central galaxy reaches a stellar mass of  $10.8 \times 10^{10} M_\odot$ , higher than current observational estimates for the Milky Way, for example  $5.5 \times 10^{10} M_\odot$  from (Flynn et al. 2006). Distributions of the different mass components, and the positions of all satellites at  $z = 0$  are shown in three orthogonal projections along the principal axes of the inertia tensor of the halo in Figure 4. By comparison with the flattened distribution seen at high redshift, the final shape of the halo appears round and largely featureless. This transformation from a triaxial mass distribution, expected from purely gravitational assembly, to an oblate halo similar to that observed, is also studied in Tissera et al. (2010), who attribute the difference to baryonic effects.

### 4 FORMATION AND EVOLUTION OF SATELLITES

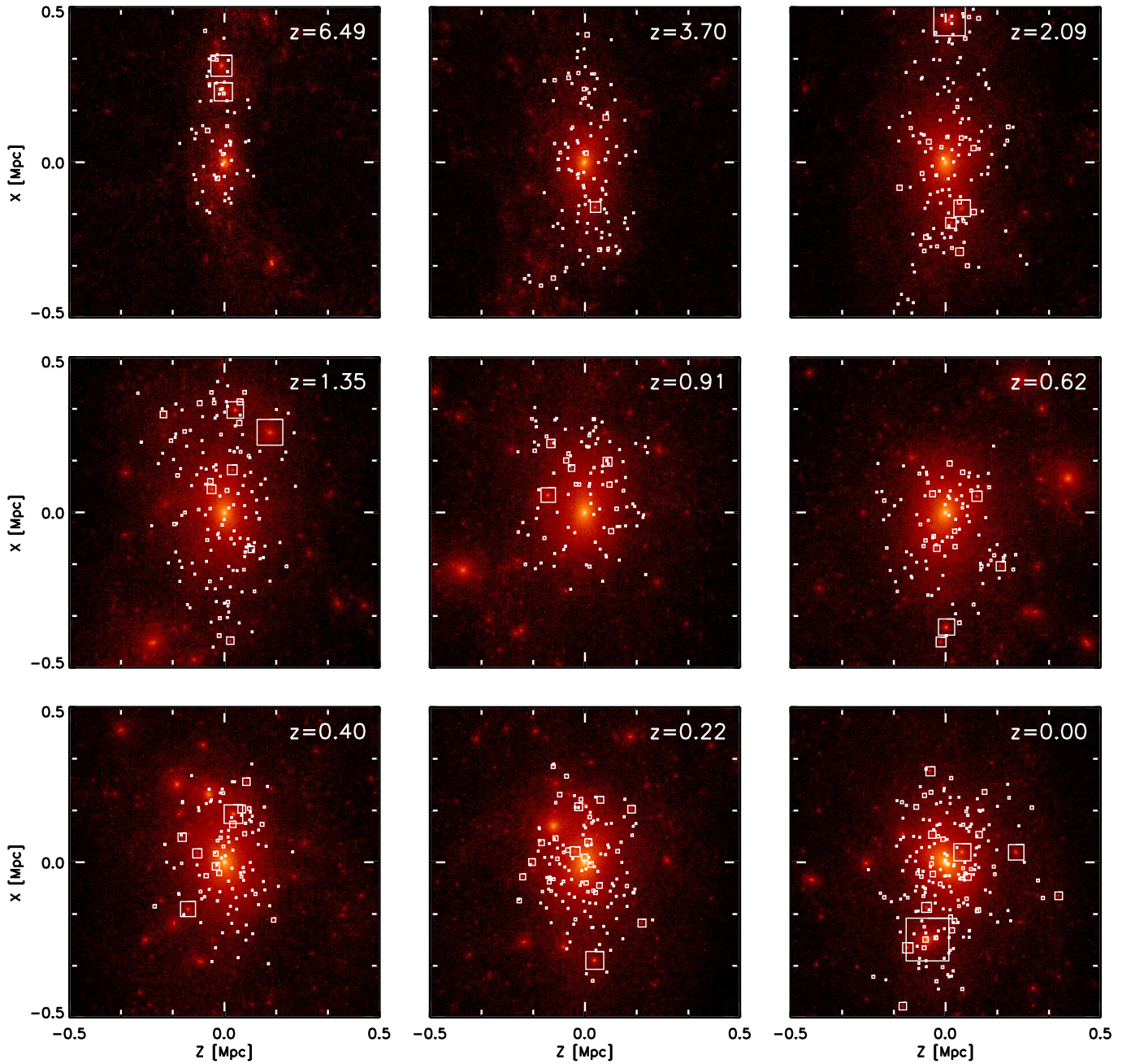
When the environment is included, different mechanisms of gas loss can play a role, and all are observed in the simulation. Internal and external mechanisms often act simultaneously, and are not always easy to disentangle. Just as supernova heating aids in the gas removal by UV radiation (Sawala et al. 2010), the thermal expansion caused by the energy input can also make it easier for tidal interactions to remove gas. In section 4.1, we discuss four exemplary cases of gas loss which are representative of the total subhalo population in terms of their final properties, but where the different mechanisms are relatively easily identified. Section 4.2 considers two extreme cases of subhaloes very heavily affected by stripping. Section 4.3 describes four satellites that still contain gas at  $z = 0$ , and contrasts them to the many gas-free satellites.

#### 4.1 Gas Loss by Example

In the top panel of Figure 5, we show the evolution of the three mass components, dark matter (black), gas (blue) and stellar mass (green) of 4 selected subhaloes, each representing a different evolutionary path. Also shown in the bottom panel of Figure 5 is the distance from the satellite centre of mass to the main halo centre as a function of redshift.

- First from the left in Figure 5 is subhalo 14. Here, the gas is blown out by the combined effect of supernova feedback and UV heating while the dwarf halo is still in isolation. As it approaches the central halo, some gas is re-acquired at  $z \sim 3.5$ , but this does not lead to renewed star formation. This residual gas is lost when the dwarf halo finally





**Figure 1.** Evolution of the dark matter distribution in the central region of the Aquila simulation. Each panel shows a box of sidelength 1 Mpc (comoving), centred on the central subhalo, and oriented along the major (X) and minor (Z) component of the inertia tensor of the main halo. The squares show the position of identified subhaloes belonging to the FoF-group of the main halo present at each snapshot, with the area proportional to the subhalo mass. Over time, the distribution of mass and of subhaloes changes from an elongated distribution at high redshift to a more rounded distribution at lower redshift (different projections of the subhaloes at  $z = 0$  are shown in Figure 4).

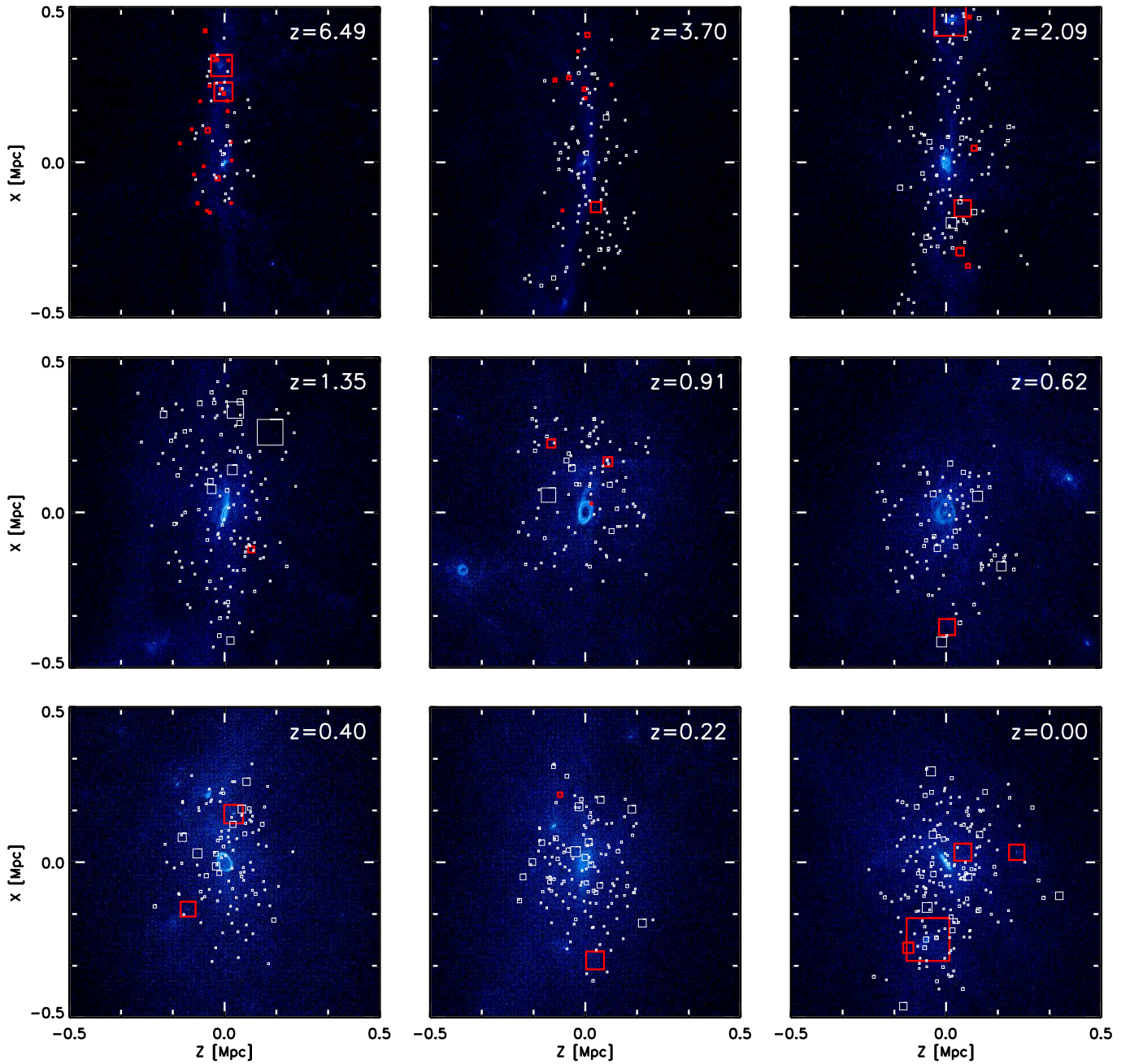
falls in to the central halo at  $z = 2.1$ . As it spirals inwards on multiple orbits, the dark matter mass decreases from its peak of  $2.4 \times 10^9 M_\odot$  to its  $z = 0$  value of  $1.3 \times 10^9 M_\odot$ . On each of the two final pericentre passages, the stellar mass also decreases slightly.

- Second from the left, subhalo 23 loses its gas already at high redshift while still in isolation, in the same way as

subhalo 14. It evolves passively and free of gas from  $z = 3$  onwards, first falling into the main halo at  $z = 1.53$ . The dark matter mass and stellar mass are not significantly affected by tides between infall and  $z = 0$ .

- Subhalo 25, in the third column, keeps a significant amount of gas and continues to form stars up to its first infall at  $z = 0.96$ . The ISM is stripped before it reaches peri-





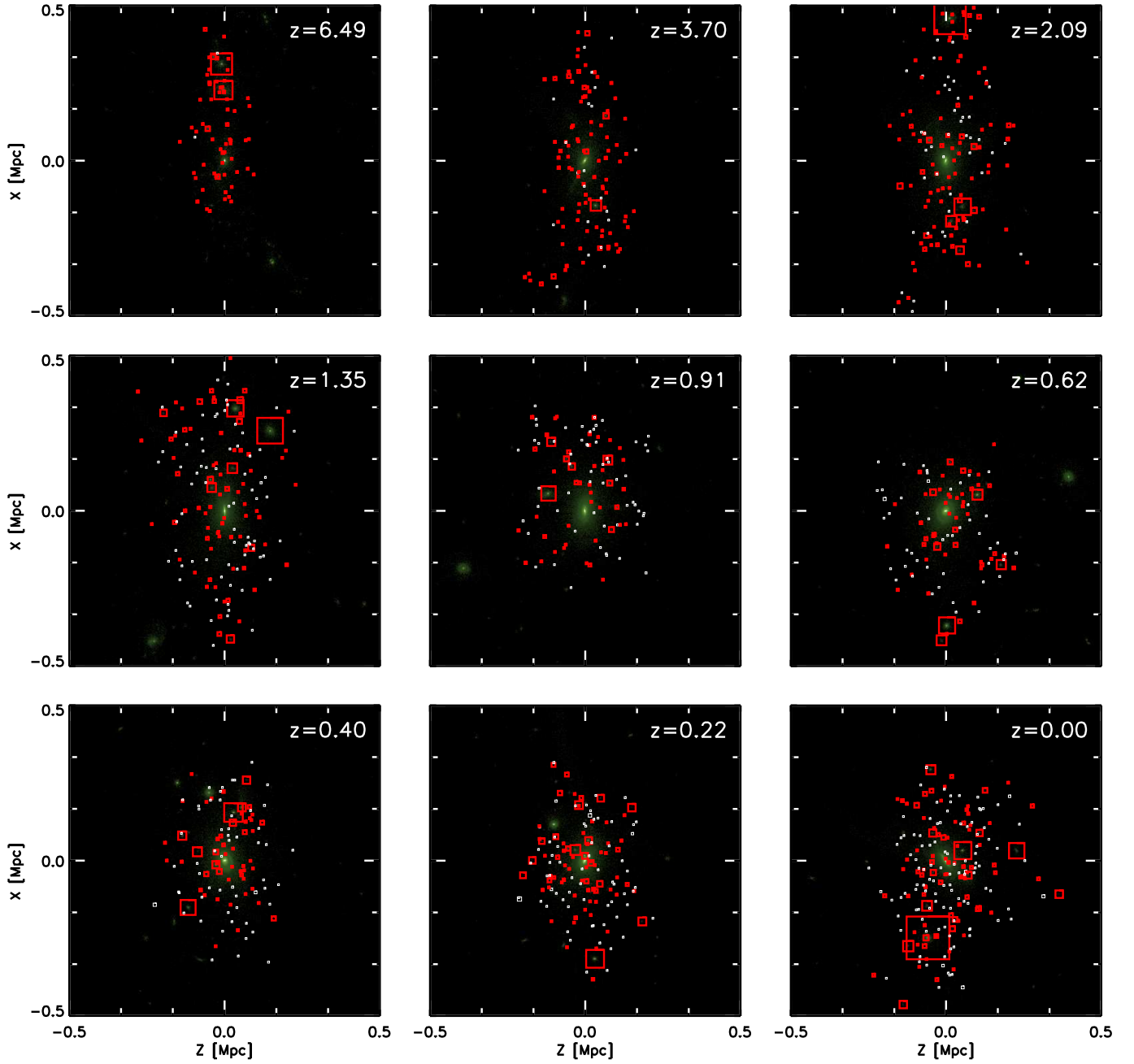
**Figure 2.** Gas distribution in the central region of the Aquila simulation at different redshifts, in volumes identical to Figures 1 and Figures 3. Subhaloes of the main FoF halo with gas are shown as red squares, Gas-free subhaloes are shown in white. While most satellites contain gas at  $z = 7$ , this fraction drops significantly, and only four of the most massive satellites are not gas-free at  $z = 0$ .

centre for the first time and star formation ceases. The dark matter mass is subsequently reduced from its peak value of  $4 \times 10^9 M_\odot$  to  $6.6 \times 10^8 M_\odot$  on two close pericentre passages. The stellar mass also decreases, particularly during the second passage.

- On the right, subhalo 56 is a peculiar case. Having lost some gas due to supernova feedback, the remainder is lost almost instantaneously at  $z = 6$ , when the effect of the UV background sets in. As for subhalo 14, a small amount of gas gets re-accreted and is lost again as the subhalo approaches

the central halo. The galaxy first becomes a satellite at  $z = 2.0$ , but does not get close to the centre on its first orbit, resulting in no stripping of stars, and only a small reduction of the dark matter mass. The final two passages are much closer, and as a result, the dark matter and stellar mass are both significantly reduced.

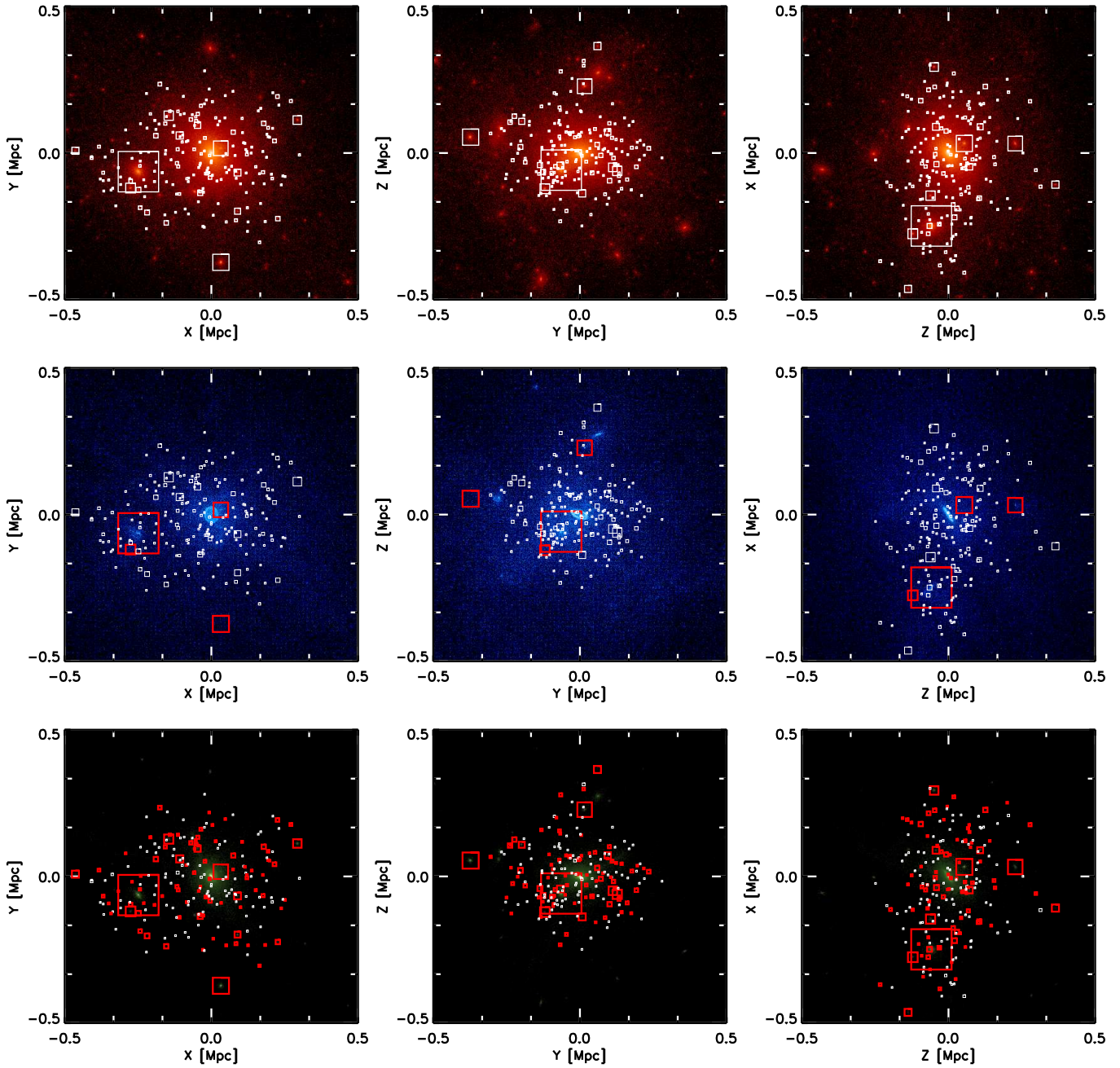
Three of the four objects have peak dark matter masses between  $7 \times 10^8$  and  $2.5 \times 10^9 M_\odot$ , with subhalo 56, which loses its gas due to UV heating, has a peak mass of  $5 \times$



**Figure 3.** Stellar mass distribution in the central region of the Aquila simulation at different redshifts, in volumes identical to Figures 1 and Figures 2. The central, Milky Way type galaxy dominates the total stellar mass at every redshift. The positions of satellite galaxies are shown in red, while dark subhaloes are shown as white squares. The size of each square corresponds to the dark matter mass of each subhalo. While nearly all subhaloes present at  $z = 7$  also contain stars, the fraction drops to  $\sim 45\%$  at  $z = 0$ , with more massive subhaloes more likely to contain stars.

$10^8$ . The final dark matter masses lie between  $5.8 \times 10^8$  and  $2 \times 10^8 M_\odot$ , with final stellar masses in the range of  $2 \times 10^6$  to  $4 \times 10^7 M_\odot$ , and corresponding stellar mass - total mass ratios of 50-100. The four objects follow the overall scaling relations of Figures 8 to 9, and are also similar to the isolated dwarf galaxies of Sawala et al. (2010), except for higher final stellar mass - total mass ratios for those objects most strongly effected by stripping.

Figure 6 shows the orbits of the four subhaloes described above in three different projections after  $z=1.9$ . While the four satellites are on similar orbits (in contrast to the two cases shown in Figure 7), it can be seen that only subhalo 25 (light blue curve), still has gas when it enters the main halo. The other three fall in gas-free. All four subhaloes are free of gas during most of their evolution as satellites.



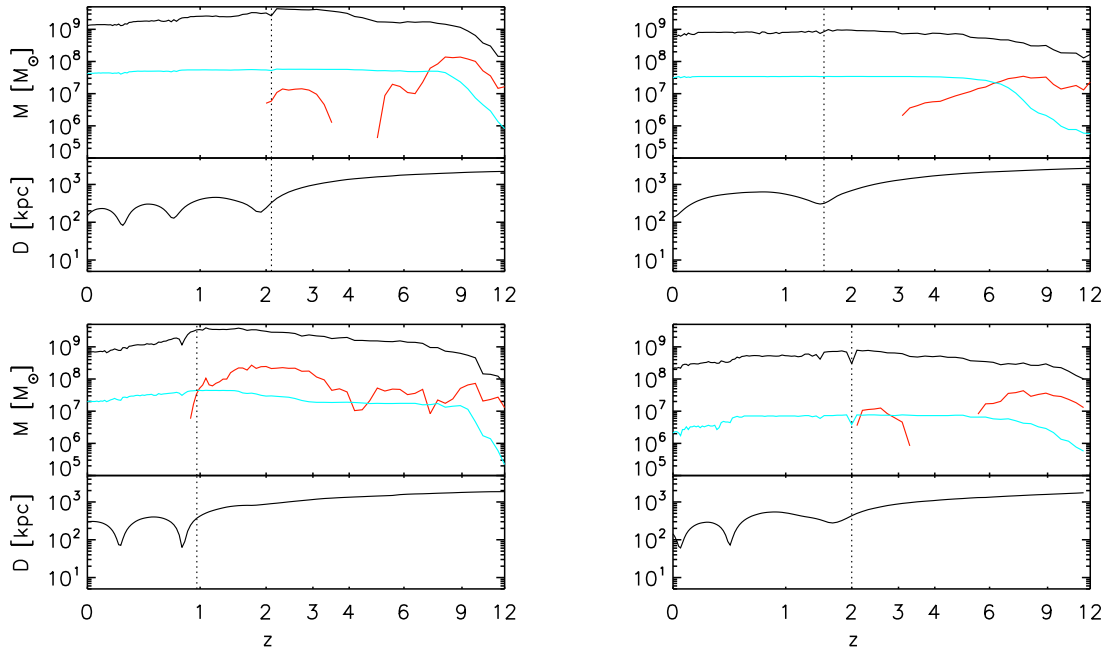
**Figure 4.** Projections of the dark matter (top), gas mass (middle) and stellar mass (bottom) distributions at  $z = 0$ , with the location of subhaloes overplotted as squares. As in Figures 1 – 3, the size of the squares indicate the dark matter mass of each subhalo. Analogous to Figure 2 and 3, in the middle row, red and white squares distinguish satellites which have gas from those that are gas-free, while in the bottom row, the distinction is between subhaloes with and without stars. Notable from the middle row is the pair of late-infalling, gas-rich satellites 1 and 7, as described in Section 4.3.

#### 4.2 Two extreme cases

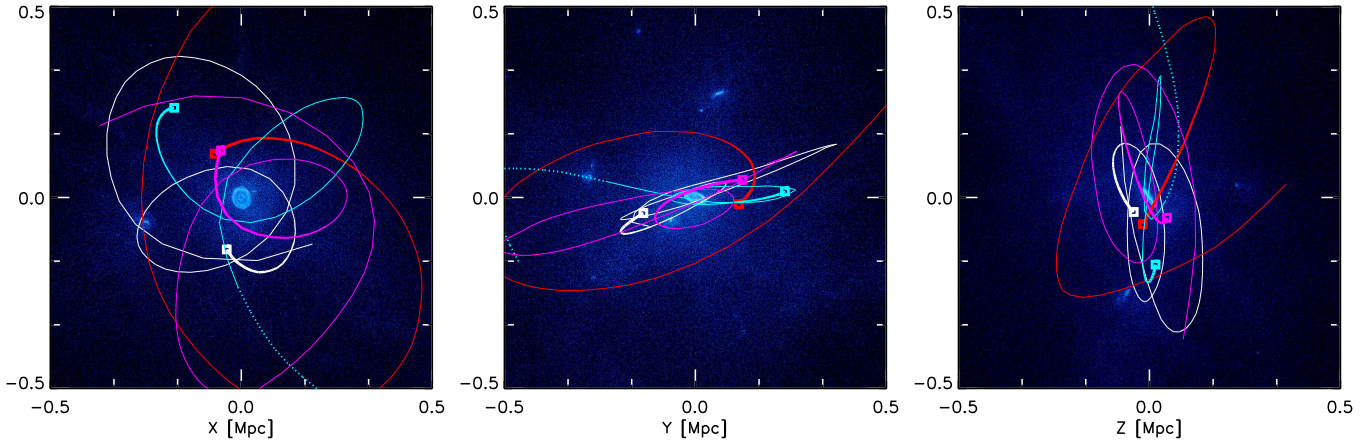
Two satellites, subhaloes 3 and 5, have final stellar masses that exceed their dark matter mass. They can be identified as outliers on the  $M_\star - M_{DM}$  relation shown in Figure 8, and are off the chart in the  $M_\star/M_{DM, z=0} - M_\star/M_{DM, infall}$  relations of Figure 9. This testifies to the fact that their dark matter masses decreased by a factor of 35 in the case of subhalo 5, and even  $\sim 200$  for subhalo 3. Not surprisingly,

the orbits of the two haloes, plotted in Figure 7, both include a number of recent close pericentre passages. A difference in orbital shape is also apparent in comparison with Figure 6. The dashed and solid line segments in Figure 7 indicate the presence or absence of gas, respectively. It can be seen that both objects still have gas when they first fall into the main halo. Interestingly, they both go through a gas-free phase on their first pericentre passage, but both recollect gas twice





**Figure 5.** Evolution of the mass components (top) and distance to the centre of the central galaxy (bottom) for four subhaloes: 14 (top left), 23 (top right), 25 (bottom left) and 56 (bottom right) as a function of redshift. In each of the top panels, the black line denotes the dark matter mass, the red line denotes the gas mass, and the blue line denotes the stellar mass. The dotted lines denote the time of infall. Before outflow and/or stripping, the galaxies reach peak baryon masses of  $\sim 5 \times 10^7$ – $3 \times 10^8 M_\odot$ , corresponding to  $\sim 2 \times 10^2$ – $10^3$  SPH particles.

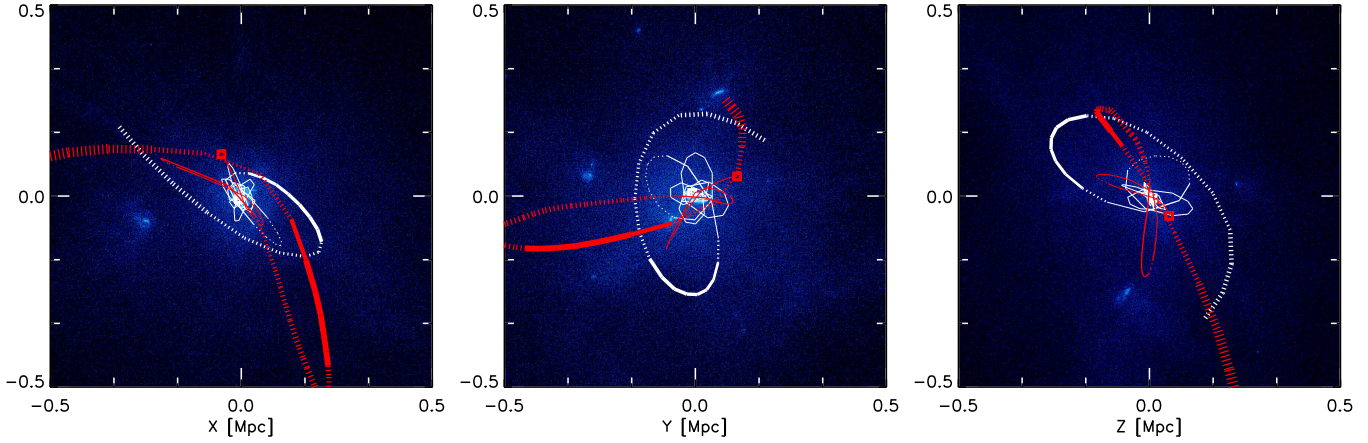


**Figure 6.** Orthogonal projections of the gas distribution at  $z = 0$ , identical to the middle row of Figure 4, together with the orbits of the four subhaloes 14 (white), 23 (red), 25 (light blue) and 56 (magenta). The square at the end of each line denotes the present position of the subhalo, while the tail end extends to  $z = 1.9$ . All four subhaloes contain stars at  $z = 0$ , but only halo 25 also contains gas until  $z = 0.8$ , as indicated by the corresponding dotted segment of the light blue orbit.

during their subsequent evolution, only to lose it again at each pericentre passage.

The two objects enter the halo with stellar mass – total mass ratios of 30 to 40 and properties similar to dwarf irregular galaxies, including gas to stellar mass ratios of order unity. They end up gas-free, with significantly reduced stellar masses, but also with final stellar mass – total mass ratios close to unity. Quantitatively, this result should be taken with caution, as the close pericentre passages make the evolution of the subhaloes also dependent on the de-

tailed properties of the simulated central galaxy. In addition, some particles belonging to the outer parts of a satellite subhalo may be misattributed to the main halo instead, even though they remain gravitationally bound, and continue to move with the subhalo. However, qualitatively, this result suggests that strong tidal stripping *decreases*, rather than increases, the total mass-to-light ratio of satellite galaxies, and is therefore not a viable way to transform gas-rich, bright dwarf irregulars into the gas-free, faint dwarf spheroidals with *high* mass-light ratios observed around the Milky Way.



**Figure 7.** Orthogonal projections of the gas distribution at  $z = 0$ , identical to the middle row of Figure 4, together with the orbits of subhaloes 3 (white) and 5 (red) after  $z = 2.45$ . Both of the subhaloes lost more than 97% of their dark matter mass since infall, and the thickness of the line changes along the orbit proportional to the dark matter mass relative to the infall mass. Dotted line segments denote the presence of gas, while solid lines indicate a gas-free phase. The squares denote the present positions of the satellites.

### 4.3 Satellite Galaxies with Gas

Something can also be learned about gas loss by considering the four satellites (subhaloes 1, 2, 4 and 7) that still contain gas at  $z = 0$ . With halo masses between  $5 \times 10^9$  and  $8 \times 10^{10} M_\odot$ , these are among the most massive subhaloes; no subhalo less massive than  $5 \times 10^9 M_\odot$  still contains gas at  $z = 0$ . None of these four satellite galaxies had particularly close encounters with the central galaxy, the minimum distance range from  $\sim 80$  to 330 kpc. However, this does not clearly separate them from the gas-free satellites, many of which are on even less bound orbits, or already fell in gas-free. The present galactocentric distances are also not significantly different among the two sub-populations.

Interestingly, two of the only three satellite galaxies which are more massive than  $5 \times 10^9 M_\odot$  and gas-free, are hosted in subhaloes 3, 5, which underwent particularly strong tidal interactions and were discussed in more detail in Section 4.2. Thus, it appears that maximal total masses of a few  $\times 10^9 M_\odot$  and orbits which avoid the inner halo are both required to retain any gas at  $z = 0$ . Equivalently, masses below a few  $\times 10^9 M_\odot$  or very close orbits, are both sufficient to produce gas-free satellite galaxies. If the majority of dwarf spheroidals reside in subhaloes with masses below  $10^9 M_\odot$  at present as well as at infall, cases of orbital metamorphosis are rare.

It is also worth noting that the most massive surviving satellite (subhalo 1), fell in as late as  $z = 0.13$ , and did so together with subhalo 7, another gas-rich companion. The two can easily be identified in Figures 1 to 3, where both are visible only in the last panels. It has been noted previously that the presence of two satellites as bright as the Magellanic Clouds near the Milky Way is rather unusual in  $\Lambda$ CDM (e.g. Boylan-Kolchin et al. 2010). Tremaine (1976) showed that dynamical friction in the halo of the Milky Way would lead to a rapid decay of the orbits of such large satellites, which would therefore be short-lived, surviving only a few Gyrs. Proper motions (e.g. Besla et al. 2007; Piatek et al. 2008) suggest that the Magellanic Clouds are indeed near their first pericentre after infall.

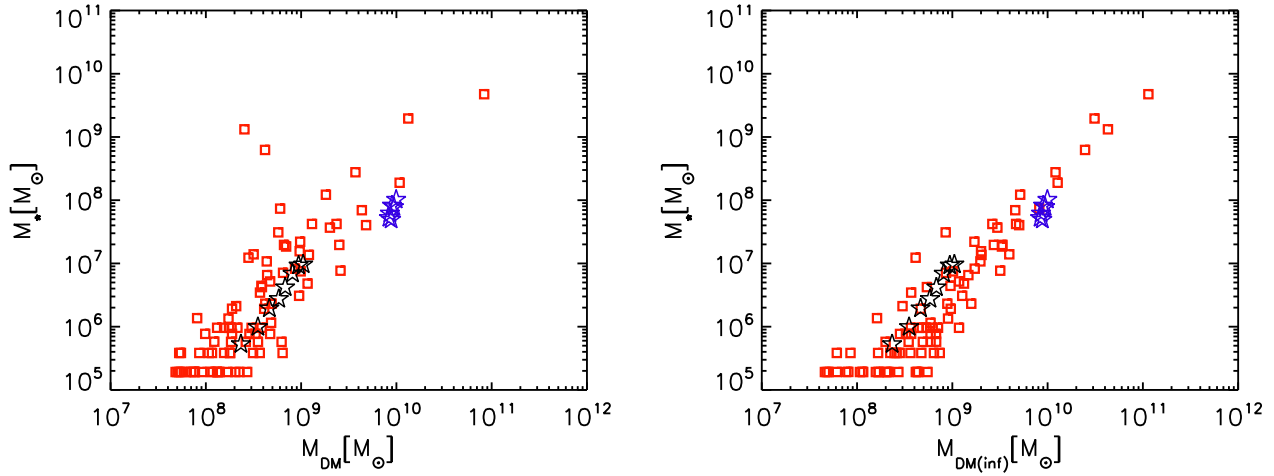
## 5 SCALING RELATIONS

At redshift  $z = 0$ , the halo contains 199 satellite subhaloes, with masses between  $10^{11}$  and  $10^8 M_\odot$ . Of these, 90 have stars, and 4 also contain gas. The properties of all satellites are listed in Table 1 of the appendix. They include the present stellar, gas and dark matter mass, the present galactocentric distance and the distance of closest approach, the infall redshift, the mass at infall, the median and maximum stellar metallicity. In this section, we explore the scaling relations among these properties. We focus in particular on the way in which the formation and evolution of the satellite population is linked to the subhalo mass, and to the influence of the environment.

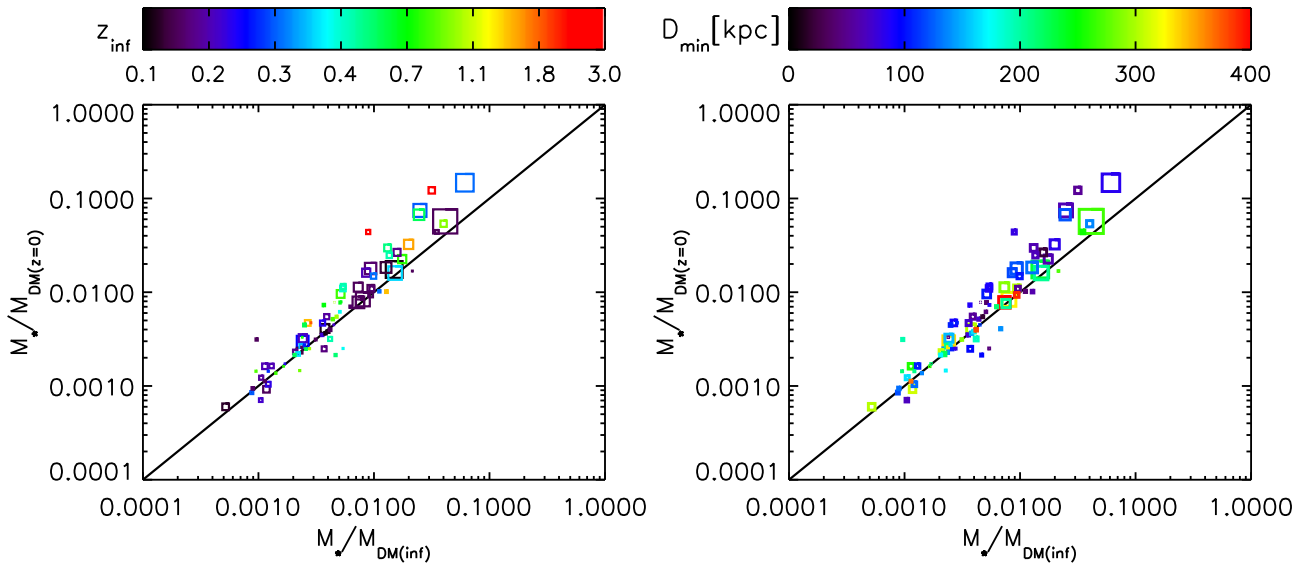
### 5.1 Stellar Mass - Halo Mass

Figure 8 shows the relationship between present stellar mass and dark matter mass for all satellites that contain stars at  $z = 0$ . In the left panel, the dark matter mass is the current mass of each subhalo, while in the right panel, the dark matter mass is the mass of the satellite at infall, i.e. when it first became a subhalo of the host halo (see Section 2.3). In both cases, there is a clear correlation of stellar mass and halo mass, indicating that the processes that determine the amount of star formation per subhalo are regulated primarily by its mass. For a halo with an infall mass of  $\sim 10^9 M_\odot$ , the corresponding stellar mass is between a few times  $10^5$  to a few times  $10^7 M_\odot$ . It should be noted that the minimum stellar mass resolved in the simulations is  $2 \times 10^5 M_\odot$ .

The two subhaloes discussed in Section 4.2, which underwent particularly strong tidal stripping, can be identified as outliers in the relation of stellar mass to present halo mass. Overall, the scatter is noticeably smaller when the mass at infall, rather than the present day mass is considered, suggesting that the evolution of the satellite after infall also plays a role in some cases. However, it is worth noting that environmental effects primarily reduce the *halo mass*, rather than the *stellar mass*, contrary to the scenario de-



**Figure 8.** Stellar mass per subhalo as a function of mass in dark matter. In both panels, red squares denote satellite galaxies in the *Aquila* simulation. The left panel shows the dark matter mass at  $z = 0$ , while the right panel shows the mass at infall. In both cases, stellar mass and total mass are clearly correlated. For comparison, the star symbols denote the results of high-resolution simulations of individual dwarf galaxies: black stars are haloes 12–20 of Sawala et al. (2010), blue stars are haloes 1–6 of Sawala et al. (2011). The smaller scatter in the relation between stellar mass and infall mass is testament to the fact that for most satellites, the stellar component is determined before infall. The scatter increases for smaller objects, and reaches about two orders of magnitude at an infall mass of  $\sim 10^9 M_\odot$ . For masses below  $10^9 M_\odot$ , an increasing fraction of haloes is completely dark. As haloes without stars are not included in these plots, this may give the false visual impression of a flattening relation or decreasing scatter at the low mass end.



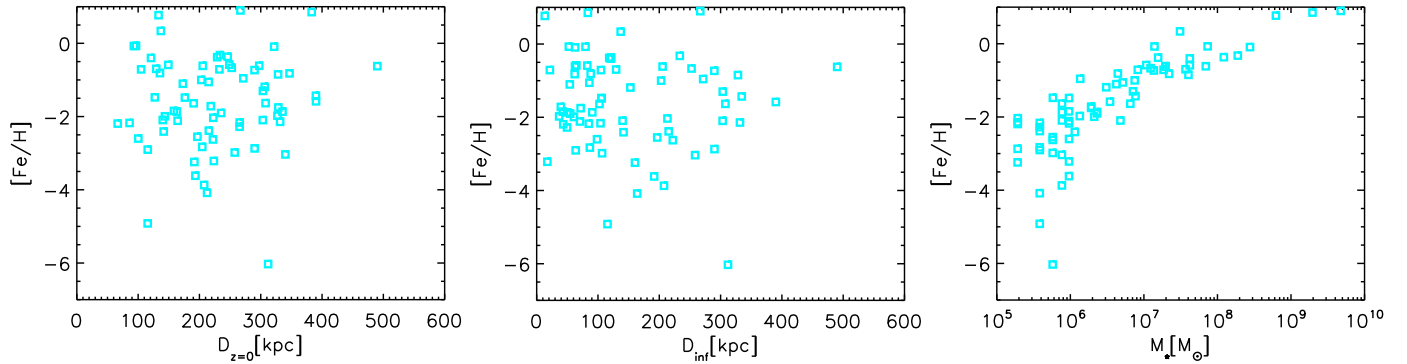
**Figure 9.** Ratio of stellar mass to halo mass of each subhalo at present, compared to the same ratio at infall. The colour coding in the left panel indicates the infall redshift of each subhalo, while the colour coding in the right panel indicates the distance of closest approach between the subhalo and the centre of the host halo. The size of the symbol is representative of the present total mass of each object. Haloes above the black line increased their stellar mass - halo mass ratio since infall, while haloes below the black line decreased it.

scribed in Section 1, whereby faint dwarf galaxies are formed through stripping of baryons.

Figure 8 also includes a comparison with results from our earlier simulations of isolated dwarf galaxies with much higher resolution. In both panels, the black stars denote results from simulations labeled 12–20, with total masses of  $2.3 \times 10^8$ – $10^9 M_\odot$ , presented in Sawala et al. (2010), with stellar particle masses of  $5.4 \times 10^2$ – $2.7 \times 10^3 M_\odot$ . Blue stars

are adopted from Sawala et al. (2011), where six haloes with representative merger histories and a common mass scale of  $\sim 10^{10} M_\odot$  were re-simulated, with a stellar particle mass resolution of  $9 \times 10^3 M_\odot$ . We find that, despite the difference in resolution of up to two orders of magnitude, the results are in good agreement between the different sets of simulations, particularly when the dark matter masses are corrected for the effect of stripping, as shown in the right





**Figure 10.** Maximum stellar iron abundance within each subhalo, as a function of present distance (left), distance of closest approach (centre), and stellar mass (right). Note that those satellites with only primordial abundances are not included. As is observed in the Local Group, there is a clear correlation of metallicity with stellar mass, but not with present position nor distance of closest approach.

panel. Because the same code has been used in all three sets of simulations, it follows that the results are not strongly affected by resolution.

The two panels in Figure 9 both show the change in stellar mass – halo mass ratio of each object from infall to the present. The ratio at infall is shown on the x-axis, while the present ratio is shown on the y-axis. Most points lie close to the black line, which indicates a constant ratio. Notably however, the majority of haloes are above the line, meaning that their stellar mass fraction has increased since infall. This can be understood as a consequence of preferential stripping of dark matter compared to stellar matter, which is more centrally concentrated and therefore more strongly bound to the satellite. In the left panel, the colour-coding is by infall redshift; black and blue symbols indicate recent accretion, yellow and red symbols indicate infall at high redshift. In general, satellites that fell in earlier are more likely to have changed their ratio since infall, as expected if the change is due to continuous tidal stripping. In the right panel, the colour-coding is done by distance of closest approach between the subhalo and the halo of the central galaxy. As expected, haloes that had closer encounters are also the ones that underwent a slightly stronger change in the stellar mass to halo mass ratio since infall. It appears that the haloes with the greatest distance ( $D_{\text{min}} > 300\text{kpc}$ ) have seen no change in the ratio, but these are commonly also subhaloes that have fallen in only recently ( $z_{\text{inf}} < 0.2$ ). In both panels, the sizes of the symbols indicate total mass; larger satellites are typically found with higher stellar mass – total mass ratios, independent of infall time or orbit.

## 5.2 Stellar Populations

Due to the small numbers of stellar particles per subhalo in the simulation, a detailed analysis of stellar populations is not possible. As a proxy for star formation history, we consider the maximum iron abundance  $[\text{Fe}/\text{H}]$  of the stars in each satellite galaxy. Because iron is formed only in the late stages of stellar evolution and injected into the interstellar medium via supernovae, the amount of iron observed in stars corresponds the specific degree of reprocessing of material within each galaxy, and the intensity and duration of star formation.

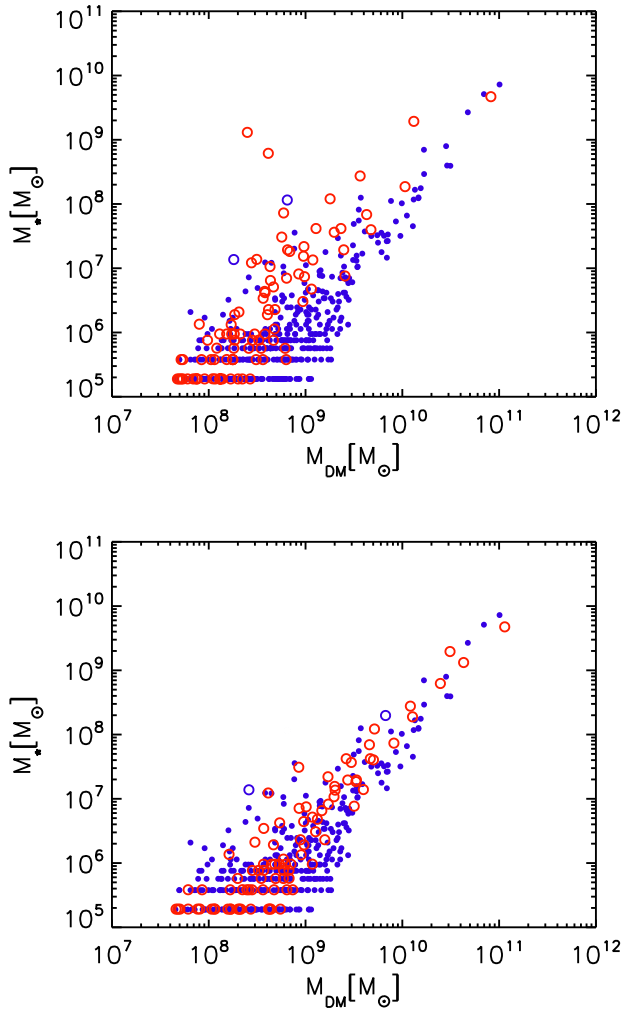
Figure 10 shows the maximum stellar iron abundance of the satellites, as a function of present distance (left), distance of closest approach (centre), and present-day stellar mass (right). Note that satellites with only a single generation of stars have primordial abundances, i.e.  $[\text{Fe}/\text{H}] \equiv -\infty$ , and therefore do not appear on the plotted relations.

The lack of a correlation on both the left and central panels indicate that the iron abundance does not depend strongly on either present distance, or distance of closest approach in the past. By contrast, there is a strong correlation with stellar mass, as observed in the Local Group, and also reproduced in our earlier simulations of isolated dwarf galaxies. At lower stellar mass, the scatter increases, similar to the trend in the relation of stellar mass and halo mass seen in Figure 8.

## 6 ISOLATED DWARF GALAXIES

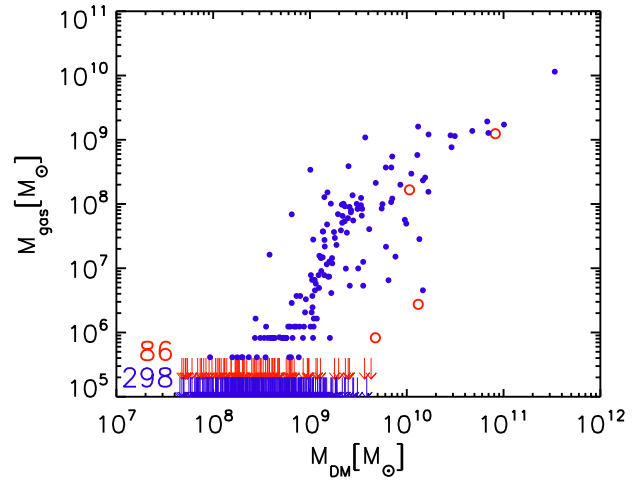
As is evident from Figures 1 through 4, the high resolution volume also contains plenty of structures outside the Milky Way halo. In this section, we compare the population of Milky Way satellites discussed in the previous section to the isolated dwarf galaxies that form in the remaining volume. At  $z = 0$ , there are a total of 2097 subhaloes in the simulation, only  $\sim 10\%$  of which are part of the most massive halo. Not all objects outside of the main group are truly isolated, as some of the other FoF groups also contain multiple subhaloes (see Section 2.3). The second largest FoF group in the simulation hosts a galaxy with a stellar mass of  $1.1 \times 10^{10} M_{\odot}$  and contains 68 additional subhaloes. The next most massive galaxy in the simulation has a stellar mass of  $1.7 \times 10^9 M_{\odot}$ . Throughout this section, we consider as *isolated* all subhaloes which are not part of the two most massive haloes. Of these 1810 subhaloes, 420 host stars, and 144 also contain gas. We compare these to the *satellites* of the Milky Way halo, that were discussed in the previous sections.

Figure 11 shows the relation of stellar mass to halo mass for satellite galaxies (in red) and for these isolated dwarfs (in blue). When the mass ratios are compared at  $z = 0$  (upper panel), the satellites contain a systematically higher stellar mass for a given halo mass compared to the isolated galaxies. The difference is reduced when the infall masses are



**Figure 11.** Stellar mass per subhalo as a function of dark matter mass. In both panels, *isolated* galaxies are shown as blue dots, *satellite* galaxies are overplotted as red, open circles. The two blue, open circles represent dwarf galaxies presently isolated, but which had past interactions, as described in the text. In the upper panel, the dark matter mass of both the isolated and the satellite galaxies is taken at  $z = 0$ , while the infall mass of the satellites and the interacting isolated galaxies is used in the lower panel, as in Figure 8. The fraction of subhaloes without stars (not shown) is 55% for the satellite subhaloes of the Milky Way, and 77% for the isolated subhaloes.

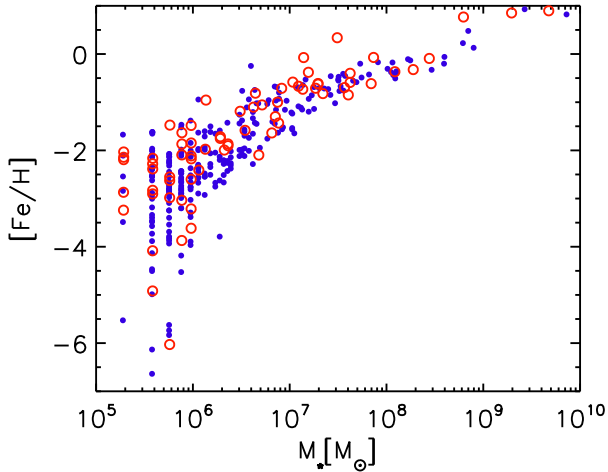
considered for the satellites (lower panel). The trend that low-mass, isolated subhaloes still show a higher mean dark matter mass in this second relation may be partly due to the fact that they typically grow in mass until  $z = 0$ , while satellites peak at  $z_{inf} > 0$ . However, it is also partly attributable to the identification of substructures, which requires a higher density if the mean background density is higher. Interestingly, in the upper panel, the population of isolated dwarf galaxies also shows two outliers in the  $M_* - M_{DM}$  relation, which are denoted by blue open circles in both panels. While these two deviate not as significantly as the satellites which were discussed in Section 4.2, it points to the fact that even some dwarf galaxies which are isolated at  $z = 0$ , may have



**Figure 12.** Gas mass as a function of present subhalo mass for *isolated* dwarf galaxies (blue) and *satellite* dwarf galaxies (red). Filled (open) circles indicate isolated (satellite) galaxies with  $M_{\text{gas}} > 0$ ; arrows show the dark matter masses of galaxies that contain stars, but no gas. The red and blue numbers indicate the total number of gas-free subhaloes with stars for the two populations. The fraction of gas-free galaxies over the mass range shown, is  $\sim 95\%$  for satellites, and  $\sim 75\%$  for isolated dwarf galaxies.

undergone interactions in the past. The two objects with high stellar to total mass ratios were never satellites of the main halo, but have interacted with smaller groups of galaxies, which also lead to tidal stripping, mostly of dark matter. In the lower panel, we plot their dark matter masses before their last interactions, which brings them closer to the relation defined by both populations. It is also worth noting that the fraction of subhaloes without stars are different among the two populations: Whereas 45% of the satellite subhaloes contain stars at  $z = 0$ , only 23% of the isolated subhaloes contain stars. This indicates that the lowest mass subhaloes, which are unable to form stars even in isolation, often do not survive to  $z = 0$  if they become satellites.

In Figure 12, we compare the gas content of satellites and isolated dwarf galaxies as a function of halo mass. As described in Section 4.3, there are only four satellite galaxies with gas at  $z = 0$ , which are found in some of the most massive subhaloes. Most of the isolated dwarf galaxies at  $z = 0$  are also gas-free, but about 1/3rd of the isolated galaxies still contain some gas at  $z = 0$ . Among the isolated galaxies, there is a sharp drop in gas mass at subhalo masses of  $\sim 2 \times 10^9 M_\odot$ . More massive isolated galaxies predominantly contain gas, less massive galaxies are most often gas-free, and resemble the satellite population. This points to a mass-threshold below which gas removal is efficient, and mostly independent of environment, while more massive galaxies can keep their gas in isolation. Close to this mass threshold, the populations differ; while some isolated dwarf galaxies still contain gas, no gas is found in the satellites. It should be noted, however, that while there are only four satellite galaxies with gas at  $z = 0$ , the total number of satellite galaxies above the mass threshold is also very low. The most massive, gas-free galaxies are found in subhaloes of  $\sim 5 \times 10^9 M_\odot$  in both the satellite and the isolated populations.



**Figure 13.** Maximum stellar iron abundance within each subhalo for isolated subhaloes (blue) and satellite subhaloes (red). There is no significant difference either in the correlation of metallicity with stellar mass or in the amount of scatter, which in both cases increases significantly at the low mass end.

Figure 13 compares the maximum iron enrichment  $[\text{Fe}/\text{H}]$  of stars in satellites and isolated galaxies, and is similar to the right panel in Figure 10. In both cases, there is a clear trend of increasing metallicity with stellar mass, with a large scatter at the low mass end, probably attributable in part to discreteness effects. At a given mass, the iron enrichment and the scatter are similar in the two populations, indicating that mass, rather than environment, is the primary determinant for the star formation history of dwarf galaxies.

## 7 SUMMARY

Before summarizing, it should be emphasized again that some of the results presented in this paper are scraping the resolution limit of the *Aquila* simulation, which was designed to study much larger galaxies. We have, however, been able to demonstrate that the results are consistent with our much higher resolution simulations of individual dwarf galaxies. The simulation is also not enough to solve all the questions pertaining to the dwarf galaxy satellites of the Milky Way; the so-called *ultra-faint* dwarfs are clearly outside the scope of the simulation, and even some of the classical faint satellites are only resolved with a handful of particles. Tidal effects, believed to be the main stripping mechanism, should not depend very strongly on force resolution. However, if ram-pressure stripping were effective in the Local Group, it would likely be severely underestimated, because the gas pressure is only poorly determined, and pressure gradients are artificially smoothed in the SPH formalism.

While the resolution is limited, it is reassuring that the properties of these galaxies tend to agree with the higher resolution simulations of isolated dwarf galaxies, and that the number of  $\sim 20 - 30$  dwarf-spheroidal-like galaxies with stellar masses in the range of  $\sim 10^6 M_\odot$  qualitatively agrees with the observational counts. At the same time, the fact

that the simulation was not *designed* to study dwarf galaxies may actually be an advantage: Considering that dwarf galaxies and Milky Way sized galaxies form in the same universe, it is only natural that they are simulated with the same realization of the physical laws and parameters.

We have described the formation of the satellite population in a cosmological simulation of a Milky Way sized halo and its environment that includes hydrodynamics, cooling, star formation, supernova feedback, enrichment and heating by the UV background. Of the 199 subhaloes with masses above  $6 \times 10^7 M_\odot$ , 90 contain stars and four also contain gas at  $z = 0$ .

We identified different mechanisms of gas-removal, both independent of environment (supernova feedback and UV heating), and caused by interactions with the host halo (tidal stripping). It was found that with a few notable exceptions, the properties of the satellites as a whole depend only weakly on environment, but very strongly on the mass of the subhalo. The satellite galaxies that contain stars follow a steep stellar mass – total mass relation, and a stellar mass – metallicity relation which are similar to those observed, and indistinguishable from those for isolated dwarf galaxies in the same simulation. The relations are also similar to those obtained by high resolution simulations of isolated dwarf galaxies (e.g. Revaz et al. 2009; Sawala et al. 2010).

In our simulation, tidal interactions after infall affect the dark matter haloes of satellites more strongly than their stellar components. The result is an average *increase* in total stellar mass – halo mass ratio, or a corresponding *decrease* in total mass – light ratio after infall. This is difficult to reconcile with the transformation of luminous, late-type galaxies with moderate mass-to-light ratios into dwarf-spheroidals with the high mass-to-light ratios inferred from observations, and required from abundance-matching arguments (e.g. Guo et al. 2010). Furthermore, the trend of decreasing mass – light ratio is more pronounced for satellites on closer orbits, and with earlier infall times. This suggests that, if dwarf spheroidal galaxies of different luminosities originated from common, gas rich and bright progenitors subject to different levels of interaction, their final stellar mass after stripping would scale *proportional* to their total mass – light ratio; the opposite of which is commonly inferred from observations.

Peñarrubia et al. (2010) have shown in purely gravitational simulations that preferential stripping of stars may be possible in a Milky Way potential if the infalling satellite haloes are cusped, so that the dark matter is more concentrated than the stars. Unfortunately, our fully cosmological, hydrodynamical simulations fall short of resolving the inner parts of satellite subhaloes to distinguish between cusped and cored profiles by several orders of magnitude, but the softened potential acts as an *effective* core. While the direct observational evidence for cusps or cores in dwarf spheroidals is still not clear, it should be noted that cores are not necessarily unique to “warm” dark matter: as shown by Navarro et al. (1996), and recently confirmed in simulations by Governato et al. (2010), baryonic feedback processes may result in cores in low-mass, cold dark matter haloes. If cores are a universal feature of dwarf galaxies, the transformation of dwarf irregulars to dwarf spheroidals purely via tidal effects would be difficult to reconcile with our results.

Instead, we find that satellite galaxies that end up with



high total mass-to-light ratios at  $z = 0$  are already faint on infall, and many of them have already lost their gas as a result of supernova feedback and UV radiation. While tidal interactions can remove remaining interstellar gas, as we observe in several cases, all these results suggest that the star formation of dwarf spheroidal galaxies is mostly determined independent of environment, and very strongly dependent on mass.

At a total mass of  $\sim 1 - 3 \times 10^9 M_\odot$ , the populations of isolated and satellite dwarf galaxies differ in the fraction of galaxies with gas. Whereas all satellite galaxies in this mass range are gas-free, isolated galaxies show a sharp decline in gas fraction, but many of them still contain gas at  $z = 0$ . Qualitatively, this is in agreement with the HI mass-distance relation reported by Grebel et al. (2003) and Geha et al. (2006). In the mass regime of dwarf spheroidals, however, with stellar masses below  $10^7 M_\odot$  and inferred dynamical masses below  $10^9 M_\odot$ , both the satellites and most of the isolated dwarf galaxies are gas-free. Consequently, the dwarf spheroidal galaxies formed in the simulation do not follow a clear morphology-distance dichotomy. If such a sharp relation exists, the galaxies that constitute this relationship would not only have to form in a different way compared to the simulation, but also be on different orbits, as we find that present day position is not a good proxy for past interaction.

## ACKNOWLEDGEMENTS

All simulations were carried out at the computing centre of the Max-Planck Society in Garching.

## REFERENCES

- Annibali F., Grutzbauch R., Rampazzo R., Bressan A., Zeilinger W. W., 2010, ArXiv e-prints
- Bernard E. J., Monelli M., Gallart C., Drozdovsky I., Stetson P. B., Aparicio A., Cassisi S., Mayer L., Cole A. A., Hidalgo S. L., Skillman E. D., Tolstoy E., 2009, *ApJ*, 699, 1742
- Besla G., Kallivayalil N., Hernquist L., Robertson B., Cox T. J., van der Marel R. P., Alcock C., 2007, *ApJ*, 668, 949
- Boylan-Kolchin M., Springel V., White S. D. M., Jenkins A., 2010, *MNRAS*, 406, 896
- Davis M., Geller M. J., 1976, *ApJ*, 208, 13
- Einasto J., Saar E., Kaasik A., Chernin A. D., 1974, *Nature*, 252, 111
- Faber S. M., Lin D. N. C., 1983, *ApJ*, 266, L17
- Flynn C., Holmberg J., Portinari L., Fuchs B., Jahreiß H., 2006, *MNRAS*, 372, 1149
- Geha M., Blanton M. R., Masjedi M., West A. A., 2006, *ApJ*, 653, 240
- Gilmore G., Wilkinson M. I., Wyse R. F. G., Kleyna J. T., Koch A., Evans N. W., Grebel E. K., 2007, *ApJ*, 663, 948
- Gnedin O. Y., Brown W. R., Geller M. J., Kenyon S. J., 2010, *ApJ*, 720, L108
- Governato F., Brook C., Mayer L., Brooks A., Rhee G., Wadsley J., Jonsson P., Willman B., Stinson G., Quinn T., Madau P., 2010, *Nature*, 463, 203
- Grebel E. K., 1997, in R. E. Schielicke ed., *Reviews in Modern Astronomy Vol. 10 of Reviews in Modern Astronomy, Star Formation Histories of Local Group Dwarf Galaxies.* (Ludwig Biermann Award Lecture 1996). pp 29–60
- Grebel E. K., Gallagher III J. S., Harbeck D., 2003, *AJ*, 125, 1926
- Guo Q., White S., Li C., Boylan-Kolchin M., 2010, *MNRAS*, 404, 1111
- Haardt F., Madau P., 1996, *ApJ*, 461, 20
- Johnston K. V., Zhao H., Spergel D. N., Hernquist L., 1999, *ApJ*, 512, L109
- Klimontowski J., Lokas E. L., Kazantzidis S., Mayer L., Mamon G. A., 2009, *MNRAS*, 397, 2015
- Koleva M., de Rijcke S., Prugniel P., Zeilinger W. W., Michielsen D., 2009, *MNRAS*, 396, 2133
- Koposov S., Belokurov V., Evans N. W., Hewett P. C., Irwin M. J., Gilmore G., Zucker D. B., Rix H., Fellhauer M., Bell E. F., Glushkova E. V., 2008, *ApJ*, 686, 279
- Lavery R. J., Mighell K. J., 1992, *AJ*, 103, 81
- Li Y., Helmi A., 2008, *MNRAS*, 385, 1365
- Mateo M. L., 1998, *ARA&A*, 36, 435
- Mayer L., Governato F., Colpi M., Moore B., Quinn T., Wadsley J., Stadel J., Lake G., 2001, *ApJ*, 547, L123
- Mayer L., Mastropietro C., Wadsley J., Stadel J., Moore B., 2006, *MNRAS*, 369, 1021
- Meurer G. R., Freeman K. C., Dopita M. A., Cacciari C., 1992, *AJ*, 103, 60
- Michielsen D., Boselli A., Conselice C. J., Toloba E., Whiley I. M., Aragón-Salamanca A., Balcells M., Cardiel N., Cenarro A. J., Gorgas J., Peletier R. F., Vazdekis A., 2008, *MNRAS*, 385, 1374
- Monelli M., Hidalgo S. L., Stetson P. B., Aparicio A., Gallart C., Dolphin A. E., Cole A. A., Weisz D. R., Skillman E. D., Bernard E. J., Mayer L., Navarro J. F., Cassisi S., Drozdovsky I., Tolstoy E., 2010, *ApJ*, 720, 1225
- Murali C., 2000, *ApJ*, 529, L81
- Navarro J. F., Eke V. R., Frenk C. S., 1996, *MNRAS*, 283, L72
- Okamoto T., Frenk C. S., 2009, *MNRAS*, 399, L174
- Okamoto T., Frenk C. S., Jenkins A., Theuns T., 2010, *MNRAS*, 406, 208
- Peñarrubia J., Benson A. J., Walker M. G., Gilmore G., McConnachie A. W., Mayer L., 2010, *MNRAS*, 406, 1290
- Piatek S., Pryor C., Olszewski E. W., 2008, *AJ*, 135, 1024
- Revaz Y., Jablonka P., Sawala T., Hill V., Letarte B., Irwin M., Battaglia G., Helmi A., Shetrone M. D., Tolstoy E., Venn K. A., 2009, *A&A*, 501, 189
- Sánchez-Janssen R., Méndez-Abreu J., Aguerri J. A. L., 2010, *MNRAS*, 406, L65
- Sawala T., Guo Q., Scannapieco C., Jenkins A., White S., 2011, *MNRAS*, pp 64–+
- Sawala T., Scannapieco C., Maio U., White S., 2010, *MNRAS*, pp 3–+
- Scannapieco C., Tissera P. B., White S. D. M., Springel V., 2005, *MNRAS*, 364, 552
- Scannapieco C., Tissera P. B., White S. D. M., Springel V., 2006, *MNRAS*, 371, 1125
- Scannapieco C., White S. D. M., Springel V., Tissera P. B., 2009, *MNRAS*, 396, 696
- Schwartz C. M., Martin C. L., 2004, *ApJ*, 610, 201
- Smith M. C. e. a., 2007, *MNRAS*, 379, 755
- Springel V., 2005, *MNRAS*, 364, 1105

- Springel V., Hernquist L., 2003, MNRAS, 339, 289
- Springel V., Wang J., Vogelsberger M., Ludlow A., Jenkins A., Helmi A., Navarro J. F., Frenk C. S., White S. D. M., 2008, MNRAS, 391, 1685
- Springel V., Yoshida N., White S. D. M., 2001, New Astronomy, 6, 79
- Stinson G. S., Dalcanton J. J., Quinn T., Kaufmann T., Wadsley J., 2007, ApJ, 667, 170
- Strigari L. E., Bullock J. S., Kaplinghat M., Simon J. D., Geha M., Willman B., Walker M. G., 2008, Nature, 454, 1096
- Sutherland R. S., Dopita M. A., 1993, ApJS, 88, 253
- Tissera P. B., White S. D. M., Pedrosa S., Scannapieco C., 2010, MNRAS, 406, 922
- Tollerud E. J., Bullock J. S., Strigari L. E., Willman B., 2008, ApJ, 688, 277
- Tolstoy E., Hill V., Tosi M., 2009, ARA&A, 47, 371
- Tremaine S. D., 1976, ApJ, 203, 72
- Valcke S., de Rijcke S., Dejonghe H., 2008, MNRAS, 389, 1111
- Wadepuhl M., Springel V., 2010, MNRAS, pp 1538–+
- Walker M. G., Mateo M., Olszewski E. W., Gnedin O. Y., Wang X., Sen B., Woodroffe M., 2007, ApJ, 667, L53
- Whiting A. B., Hau G. K. T., Irwin M., 1999, AJ, 118, 2767
- Xue X. X., Rix H. W., Zhao G., Re Fiorentin P., Naab T., Steinmetz M., van den Bosch F. C., Beers T. C., Lee Y. S., Bell E. F., Rockosi C., Yanny B., Newberg H., Wilhelm R., Kang X., Smith M. C., Schneider D. P., 2008, ApJ, 684, 1143

Table 1: Data for satellite galaxies in the *Aquila* simulation

Label	$M_{\star}$ [ $10^6 M_{\odot}$ ]	$M_{\text{gas}}$ [ $10^6 M_{\odot}$ ]	$M_{\text{DM}}$ [ $10^8 M_{\odot}$ ]	$M_{\text{inf}}$ [ $10^8 M_{\odot}$ ]	$Z_{\text{inf}}$	$Z_{\text{form}}$	D [kpc]	$D_{\text{min}}$ [kpc]	[Fe/H]
1	4745.17	1259.41	833.43	1142.22	0.13	9.37*	266.9	266.9	-1.06
2	1960.70	2.78	133.21	310.85	0.53	10.91	383.1	83.5	-0.94
3	1322.04	—	2.54	429.65	2.32	12.07	13.2	13.2	-0.63
4	188.92	168.56	108.16	128.96	0.07	5.23*	233.5	233.5	-1.82
5	623.97	—	4.18	247.15	2.10	15.47	133.3	13.2	-0.72
6	276.84	—	37.15	121.12	0.50	14.73	321.9	62.8	-1.49
7	40.32	0.84	48.05	50.31	0.13	13.34*	328.3	328.3	-2.21
8	69.45	—	43.37	45.73	0.70	4.67*	205.4	205.4	-1.89
9	122.04	—	18.19	51.53	1.07	12.07	246.1	121.5	-1.84
10	42.12	—	23.53	46.69	0.15	9.86	121.0	121.0	-2.05
11	19.61	—	25.15	27.30	0.13	9.37	490.2	490.2	-2.36
12	7.68	—	25.90	31.83	0.38	10.38	390.0	334.5	-2.74
13	36.82	—	20.05	29.71	0.09	8.45*	129.6	129.6	-1.95
14	42.11	—	13.00	26.31	2.20	13.34	149.3	82.6	-2.09
15	73.51	—	6.02	81.83	2.90	15.47	96.6	52.5	-1.43
16	13.64	—	12.06	20.23	0.13	16.25	289.9	289.9	-1.93
17	22.03	—	9.76	17.05	1.36	5.83*	346.9	62.0	-2.21
18	4.80	—	11.69	13.24	0.05	10.38	303.4	303.4	**
19	15.60	—	9.65	20.01	0.24	14.73	228.9	118.4	-2.16
20	7.49	—	9.89	10.16	0.13	12.07	203.0	203.0	-2.90
21	3.08	—	9.52	12.70	0.26	9.86	306.6	152.9	-2.86
22	8.26	—	8.63	17.18	1.41	7.22	104.9	104.9	-2.23
23	30.98	—	5.76	8.52	1.60	12.69	137.0	137.0	-1.40
24	18.51	—	6.96	33.16	0.18	12.07	232.6	21.6	-1.98
25	19.63	—	6.61	33.58	0.99	12.69	297.6	62.6	-1.88
26	7.10	—	6.46	8.58	0.13	8.90	303.6	303.6	-3.05
27	0.38	—	6.39	7.38	0.07	7.62	304.1	304.1	**
28	0.58	—	6.24	4.90	0.13	11.48	312.0	312.0	**
29	10.77	—	4.36	19.70	0.92	11.48	248.7	64.7	-2.32
30	5.19	—	4.73	11.78	0.85	11.48	215.0	86.0	-2.23
31	2.31	—	4.90	15.81	2.10	10.91	163.3	90.8	-2.99
32	6.54	—	4.40	14.73	0.55	8.02	190.6	102.5	-2.85
33	1.15	—	4.84	5.91	0.10	7.62	141.7	141.7	-3.05
34	0.77	—	4.73	6.74	0.24	9.37	340.2	258.5	-4.45
35	13.93	—	3.17	39.60	3.09	9.37	93.1	79.6	-1.09
36	2.31	—	4.20	8.87	0.21	8.02	235.4	54.7	-2.57
37	4.23	—	3.87	5.41	0.15	0.15	173.0	54.0	-2.19
38	4.42	—	3.83	9.57	0.92	8.45	135.6	88.1	-1.77
39	1.92	—	4.09	9.63	0.33	8.90	328.7	71.7	-3.05
41	12.32	—	2.80	4.12	0.13	10.38	252.6	252.6	-1.74
42	3.46	—	3.70	3.70	0.13	8.02	390.2	390.2	-3.30
43	0.96	—	3.85	6.22	0.17	10.91	100.3	98.4	-4.82
45	0.38	—	3.68	4.73	0.31	7.62	447.4	127.2	**
46	0.58	—	3.52	5.91	0.24	8.90	257.5	106.7	-3.36
47	0.77	—	3.33	3.70	0.18	8.02	307.9	307.9	-2.96
48	0.38	—	3.13	3.63	0.21	8.45	212.5	164.0	-4.08
49	0.96	—	3.02	3.68	0.92	12.07	193.4	191.6	**
51	0.77	—	2.87	3.26	0.65	2.74	207.7	207.7	-4.07
52	0.19	—	2.71	5.49	0.28	6.50	357.1	66.6	**
53	0.58	—	2.63	3.48	0.73	7.62	222.0	222.0	-2.86
56	2.11	—	2.08	3.00	2.10	12.07	143.7	60.8	-6.99
57	0.19	—	2.25	4.38	0.50	7.62	259.8	120.2	**
58	0.96	—	2.15	5.36	1.11	7.62	176.3	106.0	-2.62
59	1.92	—	1.88	4.66	0.53	10.38	218.5	39.5	-2.36
60	0.19	—	2.04	2.15	0.14	1.36	129.8	129.8	**
63	0.96	—	1.86	4.79	1.47	11.48	164.4	70.6	-4.77

Continued on next page...



Table 1 – Continued

Label	$M_{\star}$ [ $10^6 M_{\odot}$ ]	$M_{\text{gas}}$ [ $10^6 M_{\odot}$ ]	$M_{\text{DM}}$ [ $10^8 M_{\odot}$ ]	$M_{\text{inf}}$ [ $10^8 M_{\odot}$ ]	$Z_{\text{inf}}$	$Z_{\text{form}}$	D [kpc]	$D_{\text{min}}$ [kpc]	[Fe/H]
64	0.77	–	1.88	2.82	3.29	10.38	140.2	140.2	-4.07
65	0.58	–	1.84	1.99	0.13	7.22	196.6	196.6	-2.89
66	1.34	–	1.73	9.02	1.20	8.45*	327.3	36.7	-2.98
67	0.96	–	1.75	4.44	1.67	10.38	223.5	17.5	**
68	0.38	–	1.80	2.47	1.03	10.91	267.2	97.9	**
70	0.38	–	1.80	2.80	1.07	8.02	235.1	172.1	**
71	0.19	–	1.71	1.69	0.13	4.42	367.7	367.7	**
73	0.96	–	1.55	11.76	0.79	10.91	158.5	42.6	-2.38
74	0.38	–	1.55	2.23	1.11	1.11*	265.7	104.1	-2.16
78	0.96	–	1.31	7.07	3.71	15.47	86.0	85.1	-2.58
79	0.19	–	1.40	2.71	1.41	10.38	136.0	136.0	**
83	0.19	–	1.34	1.58	0.44	0.44*	207.3	207.3	**
84	0.19	–	1.34	2.01	1.47	8.02	251.0	214.5	**
86	0.19	–	1.31	1.69	1.53	7.22	307.0	170.2	**
87	0.58	–	1.23	6.76	2.45	7.22	127.3	105.6	-2.13
94	0.38	–	1.16	6.41	1.30	10.38	265.5	49.5	-2.28
95	0.19	–	1.18	1.16	1.36	1.36*	261.9	261.9	**
97	0.19	–	1.12	1.14	0.35	0.60	222.6	213.3	-2.03
98	0.38	–	1.07	1.66	0.18	4.17	115.7	63.7	-2.90
101	0.77	–	0.99	5.91	1.67	8.45	335.5	50.1	-2.06
105	1.36	–	0.81	1.62	0.13	11.48	271.6	271.6	-1.68
110	0.19	–	0.92	4.14	2.58	6.85	188.1	145.8	**
113	0.38	–	0.85	0.85	0.28	0.28*	115.6	115.6	-4.92
119	0.19	–	0.77	4.27	0.79	10.91	66.7	43.3	-2.19
120	0.19	–	0.77	2.08	1.67	1.82	78.8	78.8	**
123	0.19	–	0.74	0.81	0.13	10.91	331.6	331.6	-2.14
128	0.19	–	0.70	0.77	0.42	0.42*	191.7	160.4	-3.24
133	0.19	–	0.61	0.61	0.13	0.28	290.0	290.0	-2.87
147	0.38	–	0.55	0.61	0.14	0.42	215.3	215.3	-2.39
152	0.38	–	0.53	2.61	1.25	1.25*	204.6	86.8	-2.83
159	0.19	–	0.55	1.07	0.29	0.29*	271.5	74.8	**
161	0.19	–	0.53	0.50	0.04	0.04*	144.7	144.7	**
167	0.19	–	0.50	0.48	0.05	0.05*	165.1	165.1	**
177	0.19	–	0.48	0.46	0.13	0.33*	379.8	379.8	**

Notes: Col. 2: Stellar mass, Col. 3: Gas Mass, Col. 4: Dark matter mass (all at  $z=0$ ), Col. 5 : Dark matter mass (at infall), Col. 6: Infall redshift , Col. 7: Formation redshift, Col. 8: Distance to the centre of central galaxy (at  $z=0$ ), Col. 9: Distance of closest approach, Col. 10: Maximum stellar iron abundance.

Remarks: \*\* indicates that more than half of the stars have primordial abundances. – indicates that the mass of the component is zero.  $Z_{\text{form}}$  \* with an asterisk indicates the redshift of *fragmentation*, as defined in Section 2.3. A total of 109 “dark” subhaloes, without baryons, are omitted.